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RF Photonics for Beamforming and Array Applications

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Abstract – This paper was prepared for NATO's RTA Lecture Series No. 229 presented at the workshop of Optics-Microwave Interactions in September 2002. This lecture focuses on the applications of RF photonics for array antennas in signal distribution, beamforming, beam control, and antenna remoting. Examples are given to discuss the requirements, benefits, and design approaches of photonics for phased array antennas. The first demonstration of using photonics for a dual band array was conducted in 1990. Later a wide band conformal array controlled by photonics was built and tested. This example talks about the optical control of phased arrays by using fiber-optic links for RF and data remoting and a time-shift beamforming network for wide instantaneous bandwidth. Last, the talk will illustrate how photonics can be used to form a wide band feed system for multibeam arrays.

1. Background

This lecture note is supplemented with a set of vugraphs (attachment), and these charts are now summarized with the following annotations. Why RF photonics? There is growing interest in applying photonic technology to phased arrays for signal distribution, beamforming, and antenna remoting [1-6]. Recently, significant progress has been made in the reduction of RF to optics conversion loss. As a result, antenna systems can benefit in the areas of wide instantaneous bandwidth, immunity to EMI, lower transmission loss for data remoting, and eventually reduction in size and weight as a goal.

Since 1980 Raytheon and HRL have been funded by DARPA and AFRL to demonstrate several wide band arrays and feed networks using photonic technology. The concept of wide band arrays centers on the usage of a true time delay beamforming network. A large array is usually divided into many subarrays, with each subarray supported by a programmable delay line. Within each subarray, phase shifters are used on the element level, where 360 degree phase shift is provided to tilt the wave front for a given scan angle.

The first dual band array (X- and L-band) was demonstrated in 1990. The L-band array has 8 elements while the X-band array has 32 elements. Each array was divided into four subarrays. A four-channel fiber optic true time delay feed network was built to scan the beam for both frequency bands. The delay line is a 3-bit assembly consisting of a 1:8 divider with 8 lasers followed by eight fibers with different precut lengths. Scan performance will be shown to illustrate that there is no beam squint (angular change) when the frequency was switched from one band to the other by using the same set of photonic delay lines for beam steering.

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After the first demonstration, a more sophisticated photonic array antenna was built and tested. The purpose of this project was to study the issues and determine the feasibility of integrating all the key photonic components into an array for system applications. The design and the wide band performance of an L-band 96-element array controlled by photonics will be discussed. The 2-D array developed for technology demo consists of 96 wideband elements, grouped into 24 columns, with each column steered by an 11-bit time shifter. The L-band array (850-1400 MHz) is capable of transmitting and receiving over ± 60° scan in the azimuth plane. It is controlled by RF and digital fiber optic links from a remote site. The design parameters of the photonic array are:

Aperture size	~ 1 x 2.7 m, conformal, 3 m radius
Frequency	L band, 850 - 1400 MHz
Bandwidth	50% at 1125 MHz center frequency
Radiation element	printed "bunny ear" elements
No. of elements	4 x 24 (96)
Element spacing	10.7 cm AZ, 21.3 cm EL
Directivity	~ 25 dBi (midband)
Beamwidth	~ 5° AZ, 15° EL (midband)
Scan limit	±60° AZ, no scan in EL
No. of T/R modules	24
Time shifters	5 bits photonic, plus 6 bits electronic
Radiated power	~ 30 W
Peak sidelobe	Transmit -13 dB AZ & EL
	Receive - 25 dB AZ, -13 dB EL

2. Photonic Beamformer

The system concept for a wideband array is quite simple -- form the beam by group delays instead of phase combining. In the 4x24 element conformal array, a T/R module with a 6-bit electronic microstrip delay line supported each column. Every three columns were combined to form one subarray, which was controlled by a 5-bit photonic time shifter. The photonic time shifter provides the long delays for the whole group of subarray, while the electronic time shifter refines the delays within one nanosecond for each column.

The system block diagram shows how the phased array is controlled by RF and digital fiber optic links from a remote site. On transmit a laser light is modulated by the RF source and transmitted through the fiber to the antenna site. The RF signal is photo-detected and amplified before it is distributed to eight subarrays. After going through the programmable 5-bit time shifter, the signal is further divided into three ways, one for each column of four elements.

The building block of the wideband beamforming network is the photonic time shift module. The programmable time shifters provide the coarse delay steps ranging from 0.25 ns to 7.75 ns for the subarrays, while the electronic delay lines in the T/R module provide fine differential delays ranging from 0.01 ns to 0.5 ns. The physical dimension of the 5-bit photonic time shift module is 10.5 x 12 x 6 cm. Key components inside the time

shifter are four semiconductor pigtailed lasers, one 4x8 fiber coupler, and two 1x4 detector arrays with FET bias switches.

During transmission, the microwave signal goes though a 1:4 RF switch and modulates one of the four lasers. The laser converts the microwave signal into light which is coupled into the 4x8 fiber coupler. After splitting by the coupler, the light is incident on all the detectors in the array. By switching on one of the 8 detectors with the bias switch, the modulated light is routed through one of the 32 preset delays before recovering the RF signal.

The RF signal is then post amplified and divided into three ways with each feeding another 6-bit time shifter in the T/R module. In the receive mode, the signal path is reversed except that the signal must be routed through two transfer switches in the photonic module so that the signal can go through the non-reciprocal 5-bit time shifter in the same direction.

In the 5-bit time shift module most of the insertion loss is incurred in the 4x8 optical coupler between the lasers and the photodetector array. The internal fan-out loss is 18 dB plus 2 dB excess loss. Further, the input impedance of the laser is only a few ohms, while the output impedance of the detector is very high, on the order of several kilo-ohms. These mismatches contribute to additional losses. To overcome these losses, matching circuits have been developed and a preamplifier and a post amplifier are usually included in the circuit to make the link appear to be transparent. Many researchers have made significant progress, and it is expected that this conversion loss will be further reduced in the future.

3. Noise Figure and Dynamic Range

Several key issues were examined in the system design and tradeoff study. The most obvious question is the impact of the high conversion loss of the time shift element on the overall noise figure of the receive system. As in a single-channel case, the overall noise figure of an array with differential weightings is primarily set by the noise figure of the LNA in each channel. Also, minimizing the front-end loss is most important because it directly affects the noise figure. This is accomplished by placing a high gain LNA right behind the radiating element. If the gain is not sufficiently large, the overall noise figure will be affected to some extent by the losses after the LNA. This is especially true for a photonic array, where the downstream loss is significant and the effect of the beam-forming network can not be overlooked.

The conversion loss of a photonic 5-bit time shifter is on the order of 40 dB without wide band input and output impedance matching. To overcome this loss, the LNA gain must be at least 45 dB or higher to reduce the overall noise figure to a reasonable level. For example, with a nominal front-end loss of 1.5 dB and a noise figure of 2 dB for the LNA, the overall system noise figure can be maintained at the level of 2.5 dB if the LNA gain is 40 dB.

The use of high gain LNA is not without limitations in terms of feedback and leakage. A lesson learned from this development is that the transfer switches in the T/R module for

the transmit and receive operation must be specially designed with very high isolation, 60 dB or more each. This results from the fact that the output of the time shifter is on the order of 0 dBm, and the power amplifier must provide 35 dB gain to boost the radiated power to two watts level specified for this application. Thus, with a 45 dB LNA, the loop gain in the T/R module is close to 80 dB, which tends to cause oscillations if the transmit and receive paths are not sufficiently isolated from each other.

There are different definitions of the dynamic range in the calculation of the radar performance. In this case, the spur free dynamic range, defined as the third order intermodulations not to exceed the noise floor, is used. Based on the beamforming network discussed, a signal to noise ratio analysis using spread-sheet program was carried out to estimate the dynamic range of the receive path.

When two amplifiers are cascaded in series, the 3rd order intercept point is somewhat degraded. To maximize the dynamic range in a cascaded system, the overall gain should be distributed properly at different stages. Lumping all the gain at the front-end is not optimal. This is especially true in the photonic array where three stages of amplification were required to overcome the loss in the receive path. In this system, an LNA in the T/R module was used to support each column; the combined output of the subarray was pre-amplified in front of the photonic time shifter, which is followed by a post-amplifier to offset the insertion loss.

Using actual device parameters in the analysis, we can optimize the dynamic range of the system to exceed 95 dB by properly distributing the gains of the amplifiers at different stages along the signal path. A high gain LNA at the front-end tends to improve the overall noise figure but reduce the dynamic range. On the other hand, a lower LNA gain will boost the dynamic range, but degrade the noise figure somewhat. Thus a tradeoff is needed to optimize the performance so that a balance on the noise figure and the dynamic range can be achieved.

Note that if the noise bandwidth increases by 3 dB the dynamic range is reduced by 2 dB, which is the two-thirds rule intrinsic to the spur free dynamic range definition. On the other hand, if the number of subarrays goes up by 15 dB, the dynamic range increases by 10 dB because the signal to noise ratio is enhanced by as much due to coherent signal combining.

Compared to an active aperture array using conventional phase shifters in the T/R modules, the optically fed array suffers about 13 dB degradation in the dynamic range due to the additional loss in the time shift module supporting each subarray. However, in spite of the high conversion loss of the photonic time shifter, many array systems can benefit from the insertion of this emerging technology to achieve wide instantaneous bandwidth, and reasonably high dynamic range at the expense of a slightly degraded system noise figure.

Now consider the effects of the conversion loss on the transmit path. The power limitations of photonic devices preclude their substitution for conventional cables or waveguides for high power distribution in the phased arrays. The concern here is how much gain is required to boost the power up to the radiation level needed for typical array

applications. Note that the maximum input power for the laser is about 10 dBm, so the input to the remote link and the time shifter is limited to this level. In the demo system, three stages of amplification were required. A post amplifier of 35 dB gain was used at the end of the remote link, followed by another post amplifier of 37 dB at the output of the time shifter. In addition, a power amplifier of 38 dB gain was used to produce one Watt radiated power for each column.

For other applications where a single channel photonic link is used with no RF fan-out loss, the transmit path will require a 10 dBm input power for the fiber optic link, followed by 30 dB post amplifier, and then a 35 dB power amplifier to produce one Watt power level at the aperture.

4. Array Performance

Antenna patterns of a nine-column test array over the specified frequency range with the beam scanned to broadside, ±30°, and ±60° showed that the beam did not squint over the bandwidth by using a true-time-delay beamforming network. A conventional array with phase shifters could not have achieved this performance.

The bandwidth of the array was studied by a new technique performed in the time domain. The basic concept is to inject a 2 ns pulse into each column of the array through a series feed and wideband couplers, and then record the waveform after the pulse propagates through all the components in the transmit or receive path. By examining the pulse shape, magnitude, and the relative time delay, we can determine the insertion loss, time delay setting, and the status of the components in each channel. This time domain reflectometry type measurement can not be used for conventional band limited arrays, but it is most suitable for a photonic time shift system.

The impulse response of a 3-column subarray consisting of 3 T/R modules and a 5-bit photonic time shifter verified that the system has a 550 MHz bandwidth, which corresponds to a range resolution of 30 cm. The pulse propagated through all the RF and optical components in the receive path, so the pulse shape revealed the true frequency characteristics of the antenna system.

The antenna patterns of the 24-column photonic array over the 850-1450 MHz band were measured. The average peak sidelobe on transmit is -15 dB, and the level on receive is -20 dB. A 10 dB edge taper was imposed on the 8:1 power combiner for the receive patterns, which produced lower sidelobes than the transmit case.

The performance of a wide band array can also be judged by its impulse response. In the antenna range test, the array was set up to receive a nono-second (500 MHz) impulse at broad side and other oblique angles. It was shown that the photonic array did not cause any waveform distortions on the impulse, while a band limited antenna with patch elements severely distort and spread the impulse. In addition, as the time shifters were commanded to cycle through various states, the impulse can be seen to shift in time domain with sub-nano-second resolution, a feature not achievable in a conventional array without a photonic true time delay feed network.

5. Multi-beam Photonic Array Feed

Photonics can also be used to support a multibeam wide band feed for array antennas. The main advantage is to reduce the complexity of the array front end. This is accomplished by replacing multiple sets of discrete phase shifters at the array element level with a simplified fiber optic Rotman lens supplemented with a RF heterodyne technique for fine scan. The feed "engine" can be used for both transmit and receive operations. On receive, the signal across the aperture is conjugatedly matched at the front end by a reverse phase gradient produced by the transmit network.

This development was motivated by the need to reduce the number of antennas on many airborne and shipboard platforms. Conventional techniques to achieve multiband and multibeam capabilities are impractical because of the size, weight, packaging density, and high cost of the beamforming networks. Packaging is difficult because of the small element spacing required for a typical 3:1 bandwidth array. It is a major challenge to package multiple sets of phase shifters, drivers, and control lines in the space available behind each element. Also, phase shifters are usually lossy, complex, and expensive to fabricate. In addition, heat dissipation imposes a heavy burden on the mechanical and thermal designs needed to achieve dense module packaging. Thus, innovative multibeam feed and independent beam scan concepts are needed.

The new beamforming system uses a simplified Rotman lens configuration supplemented with a RF heterodyne system to provide continuous scan. The configuration consists of a few feed ports to point the beams in the general directions over a ±60° range, and the heterodyne system scans the beam over a small region around the discrete offset angles. This phase-locked RF mixing feed combines the signal distribution and beam scan unit into one beamformer for both transmit and receive operations, thereby replacing the multitude of phase shifters, drivers, and beam control circuitry conventionally used. Heterodyne approaches had been studied before, but none has focused on the aspect of wide band and multibeam applications [7-16].
The basic architecture of the multifunctional, wide band beamformer will be discussed, using a 16-element array with five feed ports as an example. Each port covers a 30-degree sector over the ±60° scan range in the azimuth plane. Within any sector, each beam is steered by a heterodyne phase-locked loop, which constrains two frequencies ω_1 and ω_2 to produce a constant beat frequency, ω_0, radiated by the linear array. Frequency ω_1 is fed into the constrained lens as a reference signal. To a first order approximation, this signal provides a uniform amplitude and certain phase distribution across 16 elements along the pick-up side of the Rotman lens. The second frequency, ω_2, from an offset feed port supplies the desired phase gradient along the same 16 elements to steer the beam in the desired direction when the phase front is transferred to the array aperture. These two frequencies will mix to produce the constant ω_0. However, the spatial phase gradient is not affected by the heterodyne process. By varying ω_2 and ω_1 the phase gradient along the aperture and, hence, the beam direction, can be changed. By exciting other feed ports, one can use the same heterodyne process to generate multiple beams with different pairs of RF frequencies.

Next, the issue of bandwidth and beam broadening is considered. It can be shown that, to a first order approximation, the amount of beam squint normalized to its local beamwidth for a given bandwidth Δf_0 is given by

$$\frac{\Delta\theta_o}{BW} = \frac{N}{2}\frac{\Delta f_o}{f_{MAX}}\frac{d_R}{d_o}\,\mathrm{Sin}\theta_R\left(1-\frac{f_2}{f_o}\right) \qquad (1)$$

where N is the number of elements, f_{MAX} is the highest operating frequency of the antenna, and f_o is the current operating frequency. The element spacing is assumed to be $d_o = \lambda_{MIN}/2$ where λ_{MIN} is the wavelength corresponding to f_{MAX}. A criterion to define the bandwidth is to restrict the squint (absolute value) to be less than one quarter or one half of the beamwidth. So one can set

$$\frac{\Delta\theta_o}{BW} = \frac{N}{2}\frac{\Delta f_o}{f_{MAX}}\frac{d_R}{d_o}\,\mathrm{Sin}\theta_R\left(1-\frac{f_2}{f_o}\right)<0.5 \qquad (2)$$

to calculate the maximum size of the array (N) for a given bandwidth ($\Delta f_o/f_{max}$) in terms of feed angle θ_R, relative element spacings, and vice versa. Note that when f_2 is equal to f_0 without heterodyne, the system degenerates into a conventional Rotman lens with infinite bandwidth, consistent with the definition of a true time delay beamformer. Also, when f_2 is varied to go above or below f_o the beam will deviate from the normal setting θ_o, scanning to the right or left depending on the frequency variation. This is the basic principle of the heterodyne beam scan system.

6. Fiber Optic Implementation

The space feed can be replaced by bundles of fibers precisely cut to produce perfect wave fronts for the directions associated with the feed ports. The fiber version of the feed makes the system compact and foldable. Using light sources of different colors will provide high isolation between independent beams. A special case of the system was described in [16], in which one set of equal-line-length fibers represents the central reference port and another set of unequal-line-length fibers of incremental length ΔL generates the phase gradient required to scan the beam by frequency control through a phase-locked loop. Multibeam operation is achieved by using laser light of different colors to carry control signals for each beam while sharing the same fiber feed system. This sharing is made possible by the use of optical wavelength division multiplexers (WDMs), which allow light signals of different wavelengths to be combined, passed through the common feed system, then separated at the output to generate independent, noninteracting beams.

The transmit (TX) manifold can be used for receive by producing a conjugate phase front to mix with the incoming wave. The TX "engine" produces an outgoing wave with a slightly offset ω_0 to heterodyne with the receive signal by another set of mixers. The IF outputs at the elements can then be added in phase with a summing network and sent to the remote site by digital photonics for further filtering and processing. Again, multiple beams can share the same beamforming manifold to reduce cost and complexity. The receive signal does not go through the entire beamforming manifold in the reverse direction. Hence, the overall noise figure is not degraded by the total loss of the beamformer in the transmit path. This is especially significant when the photonic conversion loss is still high. With the new design, the receive path bypasses most of the

transmit components so the noise figure is limited only by the front-end loss and the noise figure of the LNA. This eliminates the most severe drawback encountered in other competing designs where a conventional photonic beamformer is used.

In summary, the wide band beamformer is a low-loss, compact system for simultaneous multibeam, multiband, and wide scan operation. Multiple beams can share the same optical feed manifold without duplicating the complex network of phase shifters, drivers, and beam-control data lines of a conventional feed system. Continuous beam scan by the heterodyne process eliminates the problem of gain ripple (crossover between beams) encountered in a conventional Rotman lens. Phase shifters are replaced by Wide band mixers at lower cost and less system complexity. However, more development is required to advance the technology and verify the concept.

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